THE EFFECTS OF SHOE CUSHIONING ON IMPACT FORCE DURING RUNNING

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INTRODUCTION

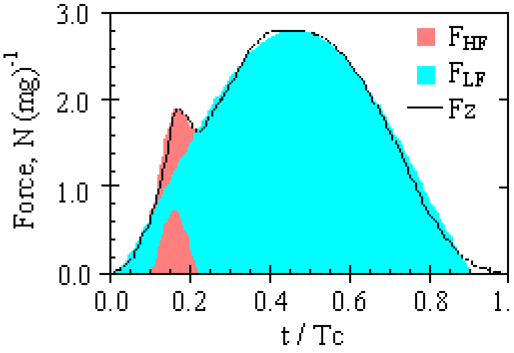
During heel-toe running in humans, the vertical component of the ground reaction force (Fz) (Cavanagh and Lafortune, 1980; Munroe *et al*, 1987) has characteristic "passive" and "active" peaks. The "passive" or "impact" peak (Fz_1) is observed within 50 ms of initial ground contact and is associated with the impact between the body and the ground. The magnitude of Fz_1 has been used as an index of impact shock, particularly in studies of running shoe cushioning. Counterintuitively, Fz_1 is not reduced by softer shoe cushioning (e.g. Clarke *et al*,1983; Nigg and Bahlsen, 1988; Snel *et al*, 1985) and may even be higher in more "cushioned" shoes (e.g. Nigg *et al*, 1987).

The absence of a cushioning effect on Fz_1 is inconsistent with other observations. *In-vitro* impact test results show reductions in impact shock that are consistent with mechanical theory. Different cushioning systems can also be distinguished by *in-vivo* in-shoe pressure measurements (Hennig & Milani, 2000), human pendulum impacts (Lafortune *et al*, 1996) and subjective perception (Milani *et al,* 1997). There is also reason to question the validity of Fz_1 as a measure of lower extremity impact. The ground reaction force reflects the vector sum of the accelerations of all the body's segments. Kinematic analysis has shown that the impact peak has its origin in lower extremity accelerations, but that its magnitude is determined by acceleration of the rest of the body (Bobbert *et al* , 1991). Lower extremity acceleration itself is a combination of low frequency "active" components and higher frequency "impact" components (Shorten and Winslow, 1993). Consequently, the magnitude of Fz_1 may not accurately quantify impact magnitude and the presumption that Fz_1 is related to lower extremity shock may not be a robust one. Therefore, the purpose of this study was to reevaluate the nature of the impact component of Fz, and how it is affected by running shoe cushioning.

TWO COMPONENT MODEL OF Fz DURING RUNNING

While spectral analysis reveals high and low frequency components in Fz signals, frequency domain methods (e.g. harmonic analysis, FFT, filter banks) cannot accurately quantify non-stationary pulses. Therefore, explicit modeling of Fz is preferable. The conceptual division of Fz into "impact" and "active" components suggests the simplest form such a model can take – a leg spring or low frequency component (F_{LF}) and an impact or high frequency component (F_{HF}), with each modeled by the impact of a mass-spring (Figure 1). The reaction force F(t) during impact of a mass-spring impact with mass m, natural frequency ω_n and impact velocity v_0 is

$$F(t) / mg = (v_0\, \omega_n / g)\, \sin(\omega_n t) + 1 - \cos(\omega_n t) \qquad (1)$$



METHODS

Fifteen male subjects (73.3 kg ± 9.0 sd) gave their informed consent and ran at 4.0 ± 0.2 m s^{-1} along a 40 m rubber-surfaced laboratory runway. Subjects completed four acceptable trials under each of four, randomly presented footwear conditions (Table 1a). Three otherwise identical shoe conditions (CS,CM,CH) had EVA midsoles of different hardnesses, approximating the 5th, 50th and 95th percentiles of available heel cushioning properties. The control condition (C0) was a "minimally cushioned" shoe with elastic sock upper, rubber outsole and thin foam insole but no midsole. Ground reaction forces from a single step of each trial were sampled at 1200 s^{-1} using a runway-mounted Kistler force plate with an Fz natural frequency of 450 Hz. Fz data from each step were normalized to bodyweight and contact time, T_C. The best-fitting, two-component model of Fz from each trial was determined using least squares minimization and an optimized search strategy.

RESULTS

Across all trials, Fz_1 averaged 2.13 BW ± 0.31 sd, with the highest values observed in the control condition. Of the three cushioned conditions, Fz_1 was highest in the CS condition (Table 1b, Figure 2). Mean peak values of Fz_1 were not significantly correlated with *in vitro* impact test results. ANOVA found significant differences among shoe conditions ($p<0.01$) but not among trials. *Post-hoc* analysis revealed that Fz_1 was significantly lower in CM than in C0. CS and CH were not significantly different from C0, nor from one another. Furthermore, Fz_1 occurred later in the stance phase under more compliant cushioning conditions. Timing differences among the experimental conditions were statistically significant ($p<0.05$), except for that between CS and CM.

On average, the two component model accounted for 98% of the intra-step variance in Fz. Peaks in F_{HF} were synchronous with Fz_1 in all but C0, where there was a statistically significant delay of 3 ms ($p<0.01$). Mean peak values of F_{HF} for each condition were smaller in magnitude than Fz_1 and were significantly correlated ($p<0.05$) with impact test Peak G scores and heel cushioning stiffness (Table 1c; Figure 2). F_{HF} was significantly higher ($p<0.5$) in C0 than in all the cushioned shoes and was also significantly higher ($p<0.05$) in CH than in CS.

Table 1: Heel Cushioning Properties and Ground Reaction Force Peaks of Four Experimental Conditions

Condition		**(a) Properties**		**(b) Fz_1 †**		**(c) F_{HF} †**	
		Peak G*	Stiffness	Peak	T_{PEAK}	Peak	T_{PEAK}
		g	kNm^{-1}	$N (mg)^{-1}$	% T_C	$N (mg)^{-1}$	% T_C
CS	"Soft"	9.6	55	2.14 ± 0.16	14.9 ± 0.8	1.03 ± 0.13	13.9 ± 0.6
CM	"Medium"	12.3	97	2.05 ± 0.15	14.3 ± 0.9	1.09 ± 0.14	13.1 ± 0.7
CH	"Hard"	15.1	152	2.05 ± 0.17	13.3 ± 0.7	1.11 ± 0.16	12.0 ± 0.6
C0	Control	25.0	439	2.28 ± 0.14	8.7 ± 0.7	1.65 ± 0.14	9.0 ± 0.5

* *ASTM F1976-99 Impact Test* † *mean ± within-condition standard deviation*

DISCUSSION

The findings of this study are consistent with previous reports showing that the Fz_1 peak occurs later in the stance phase in more cushioned shoes but that its magnitude differs little among different shoe conditions (Clarke *et al*, 1983; Nigg and Bahlsen, 1988; Snel *et al*, 1985). The trend for uncushioned shoes and those with very soft cushioning to produce higher Fz_1 scores than shoes with intermediate cushioning stiffnesses has also been previously reported (e.g. Nigg *et al*, 1987). The high frequency component F_{HF} was coincident with Fz_1 but averaged 57% of Fz_1's magnitude. Unlike Fz_1, but consistent with *in vitro* impact tests and the predictions of contact theory, F_{HF} increased with increasing cushioning stiffness.

The two-component model of Fz does not account for the inertial contributions of body segments, non-linear cushioning stiffnesses or compliance in the underlying surface. Nor does it remove the fundamental limitation of the force-plate as a cushioning evaluation tool – the ground reaction force reflects the average acceleration of the whole body, and is not specific to the lower extremity. These limitations notwithstanding, the model does serve to demonstrate that shoe cushioning affects measurable features of the ground reaction force during running and suggests an explanation for the counterintuitive effects of cushioning on Fz_1.

That explanation requires that Fz_1 is a composite of both heel impact and lower frequency force components. Assuming that shoes behave the same way *in vivo* as they do *in vitro*, softer cushioning both reduces and delays the impact peak. *In vivo*, the impact peak is summed with the low-frequency force pulse. The nonlinear summation depends on the cushioning stiffness. It tends to exaggerate the Fz_1 impact peak of softer shoes because a later impact peak is summed with a higher value of the low frequency force component.

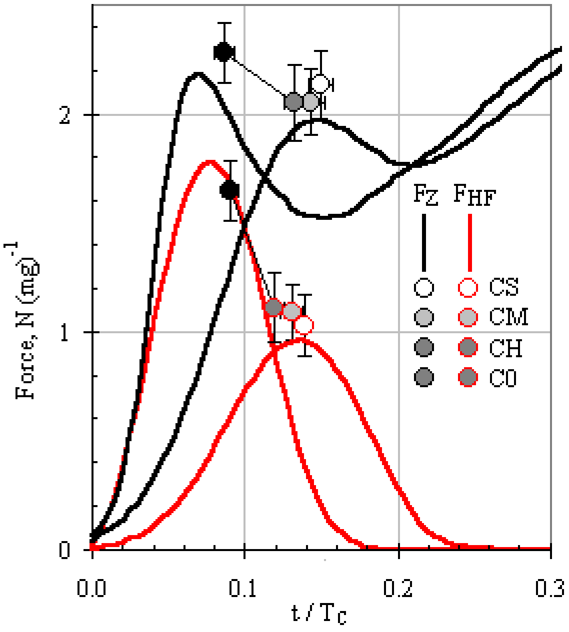


Figure 2: Average peaks in Fz and F_{HF} during initial ground contact; superimposed on ensemble averages of results from the C0 and CS conditions.

Acceptance of the suggestion that Fz_1 is not an appropriate measure of impact magnitude during running has numerous implications, not least of which is that the conclusions of previous studies using Fz_1 as a measure of cushioning effects are probably not reliable. It also implies that the effective mass involved in heel impact is less than previously calculated and that *in-vitro* impact tests based on that calculation are less valid than once thought. The hypothesis of active regulation of impact forces through kinematic adaptations would also need to be revisited.

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